CDX-U
LTX

E-beam experiments on CDX-U

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Outline

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- Experiments with evaporated lithium layers on CDX-U
  - Electron beam implementation
  - Effects of evaporated lithium coatings
  - Plasma discharges with solid lithium wall coatings

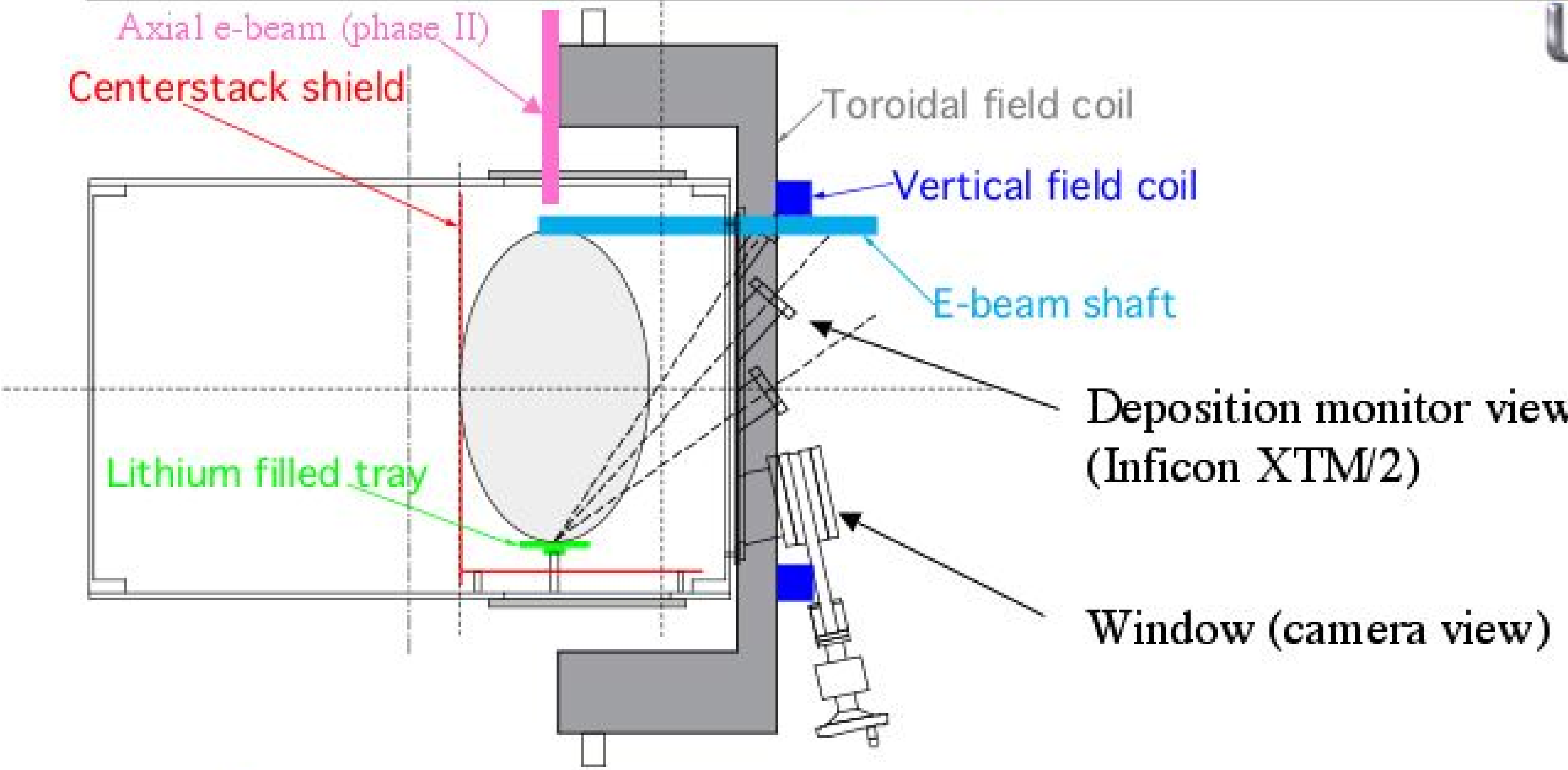
  ⇒Solid lithium wall coatings are effective at gettering oxygen

  ⇒Very low recycling conditions not obtained.
- Observations on high power density e-beam heating of thin layers of lithium

  ⇒Demonstrated power handling of 40 MW/m^2 on *static lithium* may require a re-examination of previous assumptions for the design requirements for a lithium divertor

E-beam coating experiments

CDX-U



- Electron gun first installed in CDX-U in March
  - Differentially pumped Wilson seal - long stroke to position over tray
    - Interferes with plasma; must be removed
  - TF + VF used to guide beam (~70G ea, typ.)
  - Lithium tray fill used as target.

Radial e-beam

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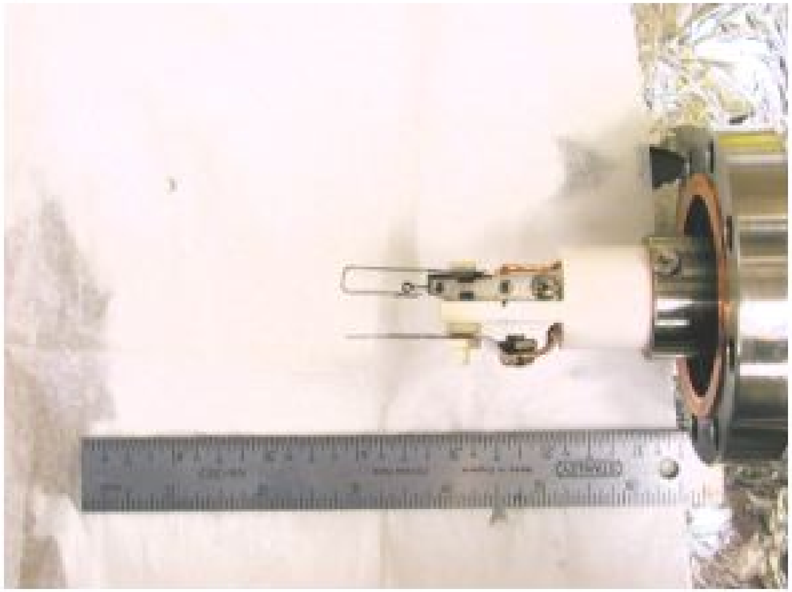
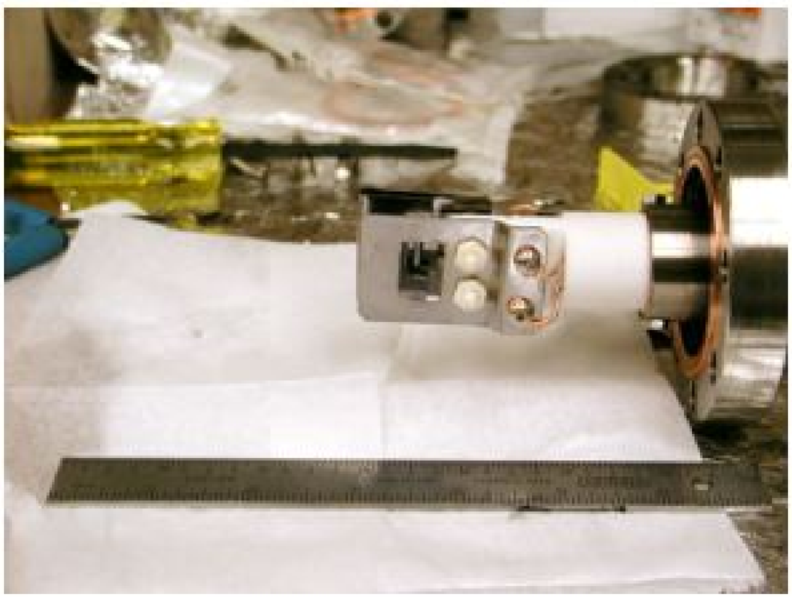
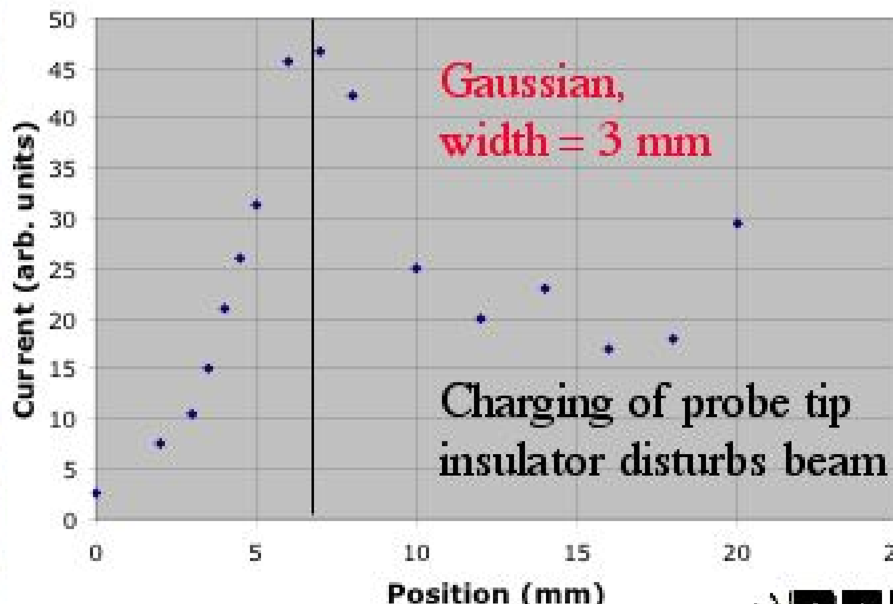
- Converted Thermionics e-gun
- Very simple beam "optics"
- 4 kV, 300 - 350 mA typ.
- 5 min. operating cycle, run at up to 50% duty factor
- Uncooled (Tantalum, Macor, SS)







Electron beam evaporation run from 4/07/05
Third 240 sec. cycle at 1.2 kW
40 MW/m^2
Produced 1000Å coating on deposition monitor at 0.9m distance
Viewing windows acquired opaque, metallic coating

Plasma operations with evaporated coatings

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- Procedure:
  - E-beam evaporation to produce a 1000 Å coating of lithium
    - » Measured at 0.9m with a quartz crystal deposition monitor
  - Retract e-beam, switch magnet power supplies
  - Setup for tokamak discharges
- Total elapsed time ~15 min. until first discharge
  - Time for many monolayers of surface coating on the fresh lithium
- Strong effect on vacuum conditions
  - Water disappears from the RGA
  - Base pressure drops by 2× (to 6-7 × 10^{-8} Torr)
- Good impurity reduction, no significant particle pumpout
  - Not a low recycling surface

Fueling comparison: bare tray, hot lithium, solid coatings

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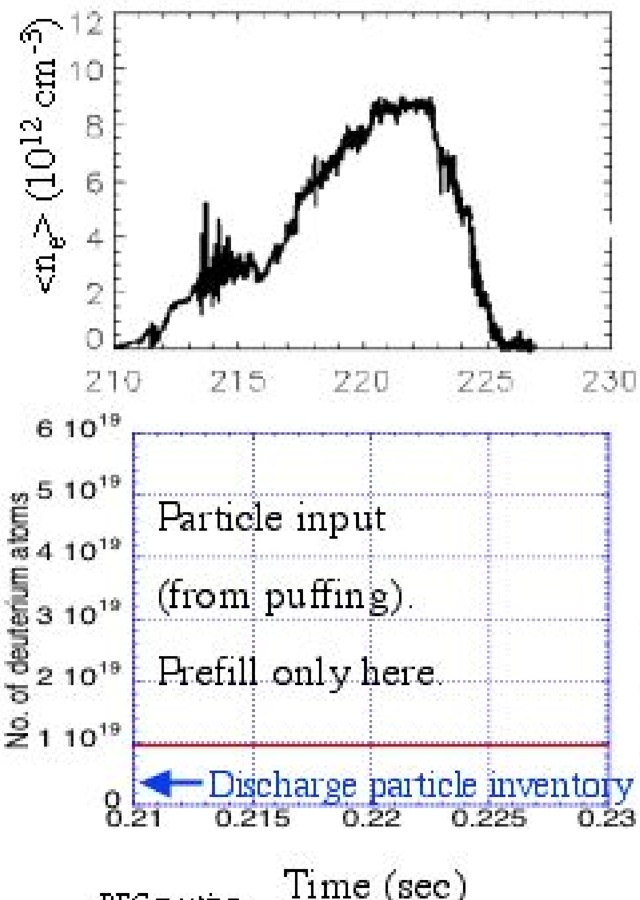
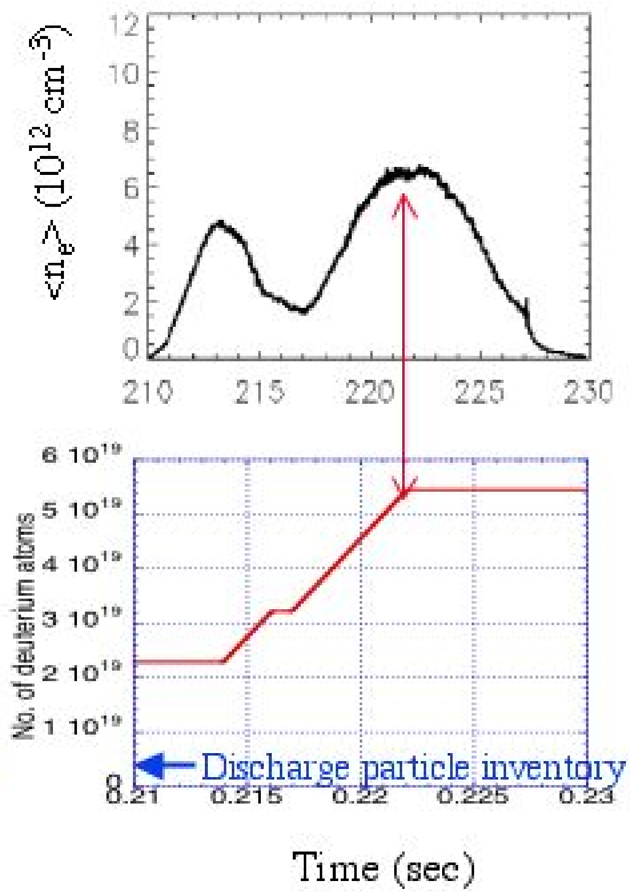
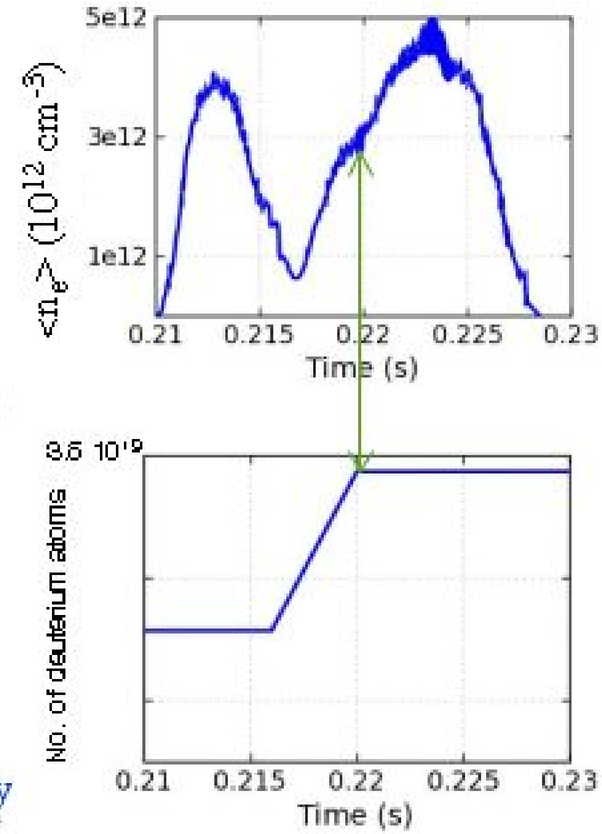
Pre-lithium (bare SS tray)



Post-lithium (liquid lithium at >300C)



Evaporated, solid Li wall coatings



Beam source design modified to permit plasma operations with beam installed

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- Axial beam orientation to allow mounting in upper port
- Beam inserted ~ 5cm past upper vessel wall
  - 5 cm behind upper rail limiter
- Guide beam to lithium with vertical field only
  - 4 kV, 300 mA

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Tray temperatures

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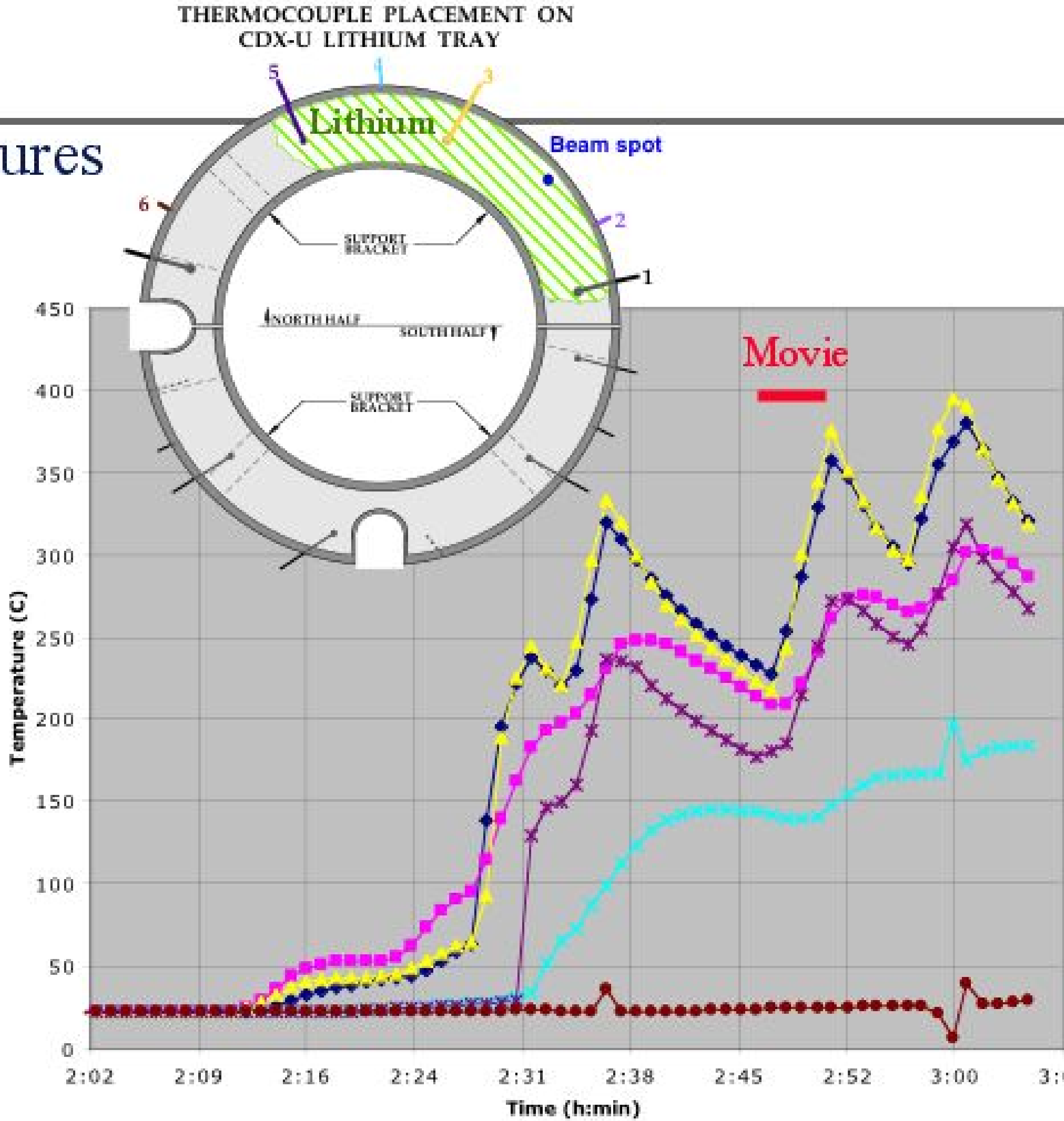

PFC meeting
9-11 May 2005
PPPL

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Electron beam evaporation run from 5/04

Third 240 sec. cycle at 1.3 kW

40 MW/m^2

~10Å coating on deposition monitor at 1.0m distance

No visible coatings on any windows

Marangoni flow, (*not thermo-conduction !!!*), controls heat transport

Surface tension gradient generates a viscous flow inside liquid lithium

Fluid Dynamics: $$\rho\frac{D\vec{V}}{Dt} = -\nabla P + \underbrace{\nu\Delta\vec{V}}_{viscosity}, \quad P = \underbrace{p}_{pressure} + \underbrace{\rho g z}_{gravity} \tag{0.1}$$

with a boundary condition (T is the surface temperature, $\vec{n}$ is a normal to the pool)

$$\nu(\vec{n}\times\vec{V})_{surface} = -\vec{n}\times\nabla\underbrace{\sigma(T)}_{\substack{surface\\tension}} = \underbrace{-\frac{d\sigma(T)}{dT}(\vec{n}\times\nabla T)}_{Marangoni\ flow\ drive}. \tag{0.2}$$

Negative $\sigma'(T) < 0$ drives the fluid away from the hot spot

Marangoni flow effects is dominant in physics of the e-beam spot heating.

- The flow establishment across the pool (several secs) is determined by

$$d_{\nu-skin} = 1.8\sqrt{t}\cdot 10^{-3} < \frac{1}{2}d_{pool\ depth}, \quad \vec{V} = 4\cdot 10^{-4}\nabla T\sqrt{t} \tag{0.3}$$

Thermal conductivity based $\nabla T \simeq 10^5$ *K°/m would give* $\vec{V} > 10$ *m/sec in a fraction of sec.*

Marangoni flow generates heat front propagation and surface waves

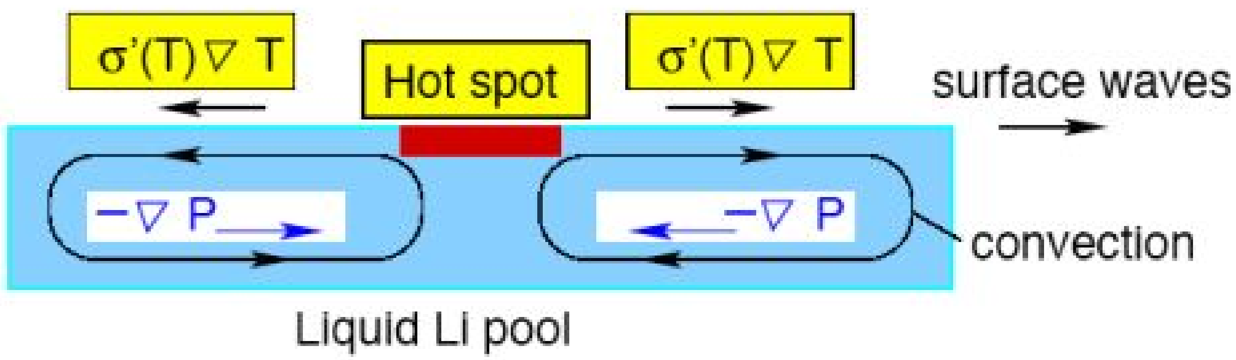
- Surface tension elevates the fluid surface and, thus, establishes the pressure gradient along the pool: $p = p(x, y)$.
- Slowly evolving convective cells are established with dominant component

$$\vec{V} \simeq V_x \vec{e}_x + V_y \vec{e}_y = \frac{\sigma'(T)}{\nu} \frac{3z^2 - 2z d_{pool\ depth}}{4 d_{pool\ depth}} \nabla T|_{surface}. \qquad (0.4)$$

mixing the heat inside the fluid and, thus, limiting ∇T.

$\boxed{\nabla T \textit{ is self-consistently determined by balancing heating and convective tranport}}$

- Convective cell region expands toward the cold fluid (or yet unmelted Li) in a form of a heat wave, melting new area and heating the fluid.
- At the same time, elevated surface of the fluid generates surface waves in the cold fluid.



Summary

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- Electron beam evaporation of lithium to produce wall coatings was far more difficult than expected
  - Entire lithium inventory is heated
  - Suggests that convective heat flow completely dominates
- Wall coatings *were* obtained with successive heating cycles
  - 1000Å at ~85 cm was selected as a "standard coating"
- Lithium "gettering" produced robust, high current discharges
  - Not low recycling
  - Time delay may play a role
- Evaporation experiments have demonstrated 40 MW/m^2 power handling capability of thin (3-4 mm) static (i.e. no forced flow) lithium films
  - Tests limited only by available power density

Issues for static liquid metal divertors

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- What is the effect of a high magnetic field?
  - CDX-U coils can only operate up to 200 - 300 Gauss for long pulse
  - Testing at 5T is desirable, with divertor-like field geometry
- Is this power handling capability limited to lithium?
  - What about tin, gallium?
- What is the peak surface temperature?
  - Surface temperature distribution?
  - IR camera highly desirable (slow is ok)
- How thin/thick can the layer be?
- What is the power handling limit for ~100 sec pulses?
- Would a thermally controlled substrate allow for steady state operation?